

# Why the Milky Way's bulge is not only a bar formed from a cold thin disk

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Accepted, Received

## ABSTRACT

By analyzing a N-body simulation of a bulge formed simply via a bar instability mechanism operating on a kinematically cold stellar disk, and by comparing the results of this analysis with the structural and kinematic properties of the main stellar populations of the Milky Way bulge, we conclude that the bulge of our Galaxy is not a pure stellar bar formed from a pre-existing thin stellar disk, as some studies have recently suggested. On the basis of several arguments emphasized in this paper, we propose that the bulge population which, in the Milky Way, is observed not to be part of the peanut structure corresponds to the old galactic thick disk, thus implying that the Milky Way is a pure thin+thick disk galaxy, with only a possible limited contribution of a classical bulge.

**Key words.** ...

## 1. Introduction

The inner regions of the Milky Way (hereafter MW) keep traces of the early phases of formation of the Galaxy, and of its subsequent evolution.

From atmospheric chemical abundance studies, we know that  $\alpha$ -enhanced, metal-poor stars are part of the bulge – the prominent out-of-the plane structure characterizing the inner few kpc of the Galaxy – and this has been interpreted as evidence of its early and rapid enrichment history (McWilliam & Rich 1994; Zoccali et al. 2006; Fulbright et al. 2007; Lecureur et al. 2007; McWilliam et al. 2008). However, chemical evolution studies also reveal that some of the stars currently in the bulge must have formed in a slower and more quiescent star formation episode, as indicated by the presence of not  $\alpha$ -enhanced, more metal-rich stars (Bensby et al. 2011; Hill et al. 2011), preferentially found closer to the Galactic plane (Ness et al. 2013a).

From stellar kinematics studies, we learn that the velocity ellipsoid of moderate metal-rich ( $[\text{Fe}/\text{H}] > -0.5$  dex), not  $\alpha$ -enhanced stars, shows a vertex deviation consistent with those stars supporting a bar-like structure (Zhao et al. 1994; Soto et al. 2007; Babusiaux et al. 2010). However, such studies also reveal that the most metal-poor,  $\alpha$ -enhanced stars are not part of this elongated structure, having velocity dispersions consistent with a kinematically hotter component (Babusiaux et al. 2010; Uttenthaler et al. 2012; Ness et al. 2013b).

Thus, observational studies suggest that the MW's bulge does not consist of a single unique component, but is rather a combination of two or more components or perhaps a continuum of populations, with different chemical and kinematic properties. Even if there is no consensus yet on the origin of

the  $\alpha$ -enhanced, metal-poor stars – classical bulge/old spheroid (Babusiaux et al. 2010; Gonzalez et al. 2011; Hill et al. 2011; Uttenthaler et al. 2012; Zoccali et al. 2014) or thick disk (Ness et al. 2013b; Di Matteo et al. 2014) – most of the above cited studies seem to agree on the thin disk origin of the not  $\alpha$ -enhanced, metal-rich component and its current structure: a bar that went through one or multiple vertical instability events in the past, which led to its current thick, boxy shape, as described by N-body models (see, for example, Combes & Sanders 1981; Athanassoula 2005; Debattista et al. 2006; Martinez-Valpuesta et al. 2006; Ness et al. 2012; Di Matteo et al. 2014).

If observational studies suggest a complex scenario for the formation of the MW's bulge, with the co-existence of multiple or a continuum of components, possibly formed at different times of the Galactic evolution, several N-body models have suggested that a pure thin disk instability model can explain sufficiently well the observed characteristics, without the need to add any significant kinematically hot component – classical bulge or thick disk (Shen et al. 2010; Martinez-Valpuesta & Gerhard 2011; Kunder et al. 2012; Martinez-Valpuesta & Gerhard 2013; Vázquez et al. 2013; Gardner et al. 2014; Zoccali et al. 2014). For example, Shen et al. (2010) analyzed a N-body simulation of a disk galaxy which developed a boxy/peanut-shaped bulge and compared it to the stellar kinematics of the bulge region, from the BRAVA bulge survey, concluding that "the model fits the BRAVA stellar kinematic data covering the whole bulge strikingly well with no need for a merger-made classical bulge". Martinez-Valpuesta & Gerhard (2013) showed that pure bar instability models are also able to reproduce

vertical metallicity gradients in the Galactic bulge, similar to those observed, provided that the initial disk had a steep enough radial metallicity gradient. They were also able to produce a longitude-latitude (hereafter  $(l, b)$ ) metallicity map remarkably similar to that constructed by Gonzalez et al. (2013) from the VVV survey, thus highlighting the result that "a simple model for the Milky Way's boxy bulge", through disk instability, is able to reproduce many of the characteristics observed in the Galactic bulge. Finally, Zoccali et al. (2014) used the N-body model presented in Martinez-Valpuesta & Gerhard (2011) and compared it with the bulge kinematics from the GIBS survey, noting that no additional kinematically hotter component needs to be added, at any latitude, to the boxy/peanut-shaped bulge to reproduce the rotation curve and velocity dispersions profiles, thus remarking that "The very good agreement between this model and the data supports the conclusion presented in Shen et al. (2010)". However, note also that in the same work, Zoccali et al. (2014) cautioned the reader about interpreting the MW's bulge as the result of a pure secular evolution process, recalling, among others, the observational evidence given at the beginning of this Section, about the composite nature of the Galactic bulge.

To conclude, none of the afore-mentioned N-body models pointed out the necessity to add an additional, kinematically hotter, component to the boxy/peanut-shaped structure, because such a simple scenario was shown to be already able to reproduce all the characteristics considered.

Thus, there is clearly a *tension between observations and their interpretation*. On the one side, pure bar instability models fit fairly well the global trends observed in the MW's bulge, without the need to invoke the presence of any additional component – and in some cases, clearly excluding it (Shen et al. 2010) on the basis of this good match. On the other side observations present a much more complex scenario, where the Galactic bulge consists of the co-existence of different populations, with different kinematic and chemical properties.

The aim of this paper is to alleviate this tension, by discussing where and why a pure bar instability mechanism operating on a thin disk fails in representing the complexity of the MW's bulge. By means of a high resolution N-body simulation of a thin disk which has undergone a bar instability, we will show that this scenario, despite explaining successfully a number of the properties of the bulge, is indeed insufficient when the detailed properties of its main populations are taken into account. We will show in particular that it is true that N-body simulations which suggest a pure thin disk origin for the MW's bulge can reproduce: *a*) the velocity rotation curve and the velocity dispersion profiles of stars in the bulge at different latitudes, as suggested by Shen et al. (2010); Kunder et al. (2012); Zoccali et al. (2014); *b*) the vertical metallicity gradient and  $(l, b)$ -metallicity maps of the bulge, qualitatively similar to observations, as proposed by Martinez-Valpuesta & Gerhard (2013) for appropriate initial conditions in the disk, *but* that these constraints alone are not sufficient to validate a pure bar instability mechanism at the origin of the MW's bulge. Such models lead indeed to bulges with properties not compatible with those observed for the MW. If the MW's bulge had uniquely a thin disk origin and it was only the result of a pure bar instability mechanism originating in a thin stellar disk with a steep enough initial radial metallicity gradient, all bulge stars (from the most metal rich to the most metal poor ones) should be part of the boxy/peanut-shaped structure. We will show that, if this was the case:

1. all red clump stars in the MW's bulge with  $[\text{Fe}/\text{H}] > -1$  dex should show a split in the distribution of their  $K$  magnitudes, which is not observed (Ness et al. 2013a);
2. the metal-poor population ( $-1 \text{ dex} < [\text{Fe}/\text{H}] \leq -0.5 \text{ dex}$ ) should be a kinematically warm replica of the more metal rich ones ( $-0.5 \text{ dex} < [\text{Fe}/\text{H}]$ ), which is not (Ness et al. 2013b).

New observational results that combine the elemental abundances and the kinematics allow us to reassess the evolutionary scenario for the bulge of the MW, and lead us to *exclude that the MW's bulge has a pure thin disk origin. This structure is not simply a thick, boxy/peanut-shaped bar formed in a kinematically cold stellar disk and seen edge-on*. Its most metal-poor ( $-1 \text{ dex} < [\text{Fe}/\text{H}] \leq -0.5 \text{ dex}$ ) population does not have a thin disk origin, as recently suggested (Martinez-Valpuesta & Gerhard 2013), but it is rather associated to an ab-initio kinematically warmer component that – on the basis of several arguments recalled in this paper – we associate to the old Galactic thick disk.

## 2. Simulations

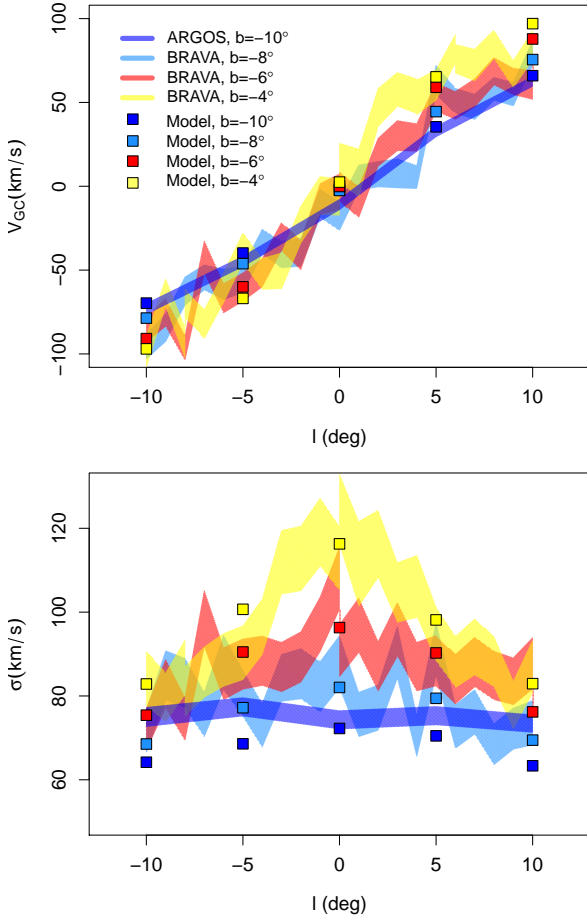
The simulation analyzed in this paper is one of a set of three high resolution simulations, with varying bulge-to-disk ratios, already described and analyzed in Di Matteo et al. (2013, 2014). It consists of an isolated stellar disk, with a  $B/D=0.1$  classical bulge<sup>1</sup>, and containing no gas. We have chosen to present in this paper the results for the simulation with  $B/D=0.1$  because this ratio is at the suggested upper limit of any classical bulge in the MW (Shen et al. 2010; Kunder et al. 2012; Di Matteo et al. 2014). However, we emphasize that the results obtained for the case with  $B/D=0.1$  are identical to those with  $B/D=0$ , making the two scenarios (pure thin disk *versus* thin disk + small classical bulge) *de facto* indistinguishable in the context of the present study. An example of this strong similarity can be appreciated comparing Figs. 9 and 12 of Di Matteo et al. (2014): adding a  $B/D=0.1$  classical bulge to the simulation has no impact on the global kinematic characteristics, neither on the velocity curve nor on the velocity dispersion profiles of the boxy bulge.

The dark halo and the bulge are modeled as Plummer spheres (Binney & Tremaine 1987). The dark halo has a mass  $M_H = 1.02 \times 10^{11} M_\odot$  and a characteristic radius  $r_H = 10$  kpc. The bulge has a mass  $M_B = 9 \times 10^9 M_\odot$  and characteristic radius  $r_B = 1.3$  kpc. The stellar disk follows a Miyamoto-Nagai density profile (Binney & Tremaine 1987), with mass  $M_* = 9 \times 10^{10} M_\odot$  and vertical and radial scale lengths given by  $h_* = 0.5$  kpc and  $a_* = 4$  kpc, respectively. The initial disk size is 13 kpc, and the Toomre parameter is set equal to  $Q=1.8$ . The galaxy is represented by  $N_{\text{tot}} = 30720000$  particles redistributed among dark matter ( $N_H = 10240000$ ) and stars ( $N_{\text{stars}} = 20480000$ ). To initialize particle velocities, we adopted the method described in Hernquist (1993). A Tree-SPH code (Semelin & Combes 2002) has been used to run the simulations. A Plummer potential is used to soften gravity at scales smaller than  $\epsilon = 50$  pc. The equations of motion are integrated over 4 Gyr, using a leapfrog algorithm with a fixed time step of  $\Delta t = 2.5 \times 10^4$  yr.

## 3. Results

In what follows, the N-body model described in Sect. 2 and extensively studied in Di Matteo et al. (2013, 2014) has been

<sup>1</sup> In the following, by classical bulge we mean a spheroidal component, not formed by disk instabilities, but rather through mergers or some dissipative collapse at early phases of the galaxy formation.



**Fig. 1.** Rotation curve (*top panel*) and velocity dispersions (*bottom panel*) of stars of the N-body models at  $|x| \leq 2.5$  kpc and  $|y| \leq 3$  kpc from the galaxy center. Four different latitudes are shown for the modeled galaxy:  $b = -4^\circ$  (yellow squares),  $b = -6^\circ$  (red squares),  $b = -8^\circ$  (pale blue squares),  $b = -10^\circ$  (dark blue squares). For comparison, BRAVA fields at  $b = -4^\circ$  (yellow curve),  $b = -6^\circ$  (red curve),  $b = -8^\circ$  (pale blue curve), and ARGOS fields at  $b = -10^\circ$  (dark blue curve) are also given. The thickness of the curves corresponds to the  $\pm 1\sigma$  error in the observational data.

rescaled to match the MW bar size and bulge velocities<sup>2</sup>. To this aim, we have divided the positions by a factor about 2, to have a bar length of about 3.5 kpc, the corotation and OLR at 4.5 kpc and 7.5 kpc respectively. With this rescaling, the Sun position is (0., -8., 0.) kpc. Velocities have been divided accordingly by a factor  $\sqrt{2}$ , so to match the rotation curve of the MW's bulge, as deduced by radial velocities measurements (see Kunder et al. 2012; Ness et al. 2013b, and Fig. 1). The bar is then observed at an angle of 20 degrees with respect to the Sun-Galaxy center direction (see for example Bissantz & Gerhard 2002).

### 3.1. Successes of a pure thin-disk bar instability scenario

The rotation curve and velocity dispersion, as deduced by radial velocity measurements, of the final model are shown in Fig. 1, together with data from the ARGOS survey for the fields at

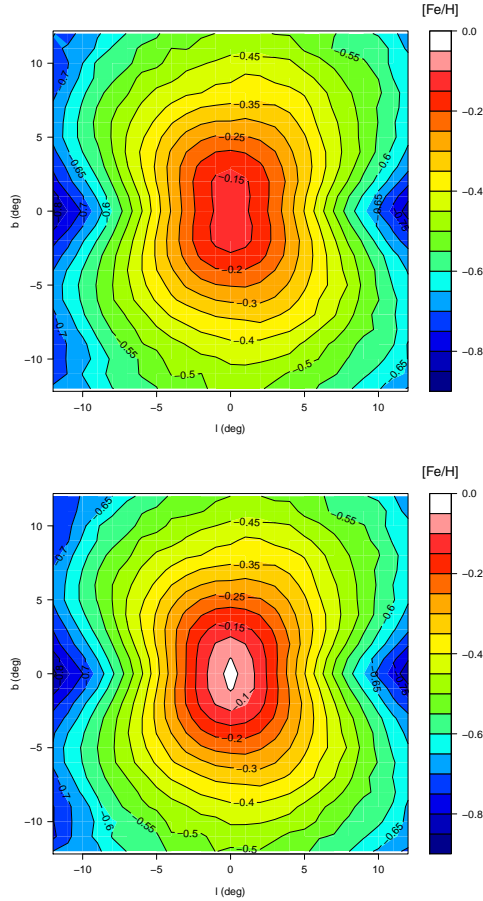
<sup>2</sup> Note that the rescaling is possible because gas is not included in the simulations.

$b = -10^\circ$  (see Ness et al. 2013b) and from the BRAVA survey for the fields at  $b = -4^\circ, -6^\circ, -8^\circ$  (Kunder et al. 2012). The simulation clearly reproduces the overall kinematic trends found for the MW's bulge, namely the nearly independence of the rotation curve with latitude<sup>3</sup> (i.e. cylindrical rotation) and the decrease and flattening of the velocity dispersions with vertical distance from the plane. Thus, in agreement with previous results (Shen et al. 2010; Kunder et al. 2012; Gardner et al. 2014; Zoccali et al. 2014), this N-body model supports the finding that a pure bar instability scenario operating on a thin disk can fit the *overall* kinematics of the MW's bulge, without the need of adding a massive kinematically hotter component (a classical bulge with  $B/D > 0.1$  or a thick disk) to explain the observed global kinematic trends.

Thin disk instability scenarios for the formation of the MW's bulge have been shown to be successful also in generating vertical metallicity gradients and metallicity maps consisting with observations. In particular, Martinez-Valpuesta & Gerhard (2013) have shown that stars in a bar can keep memory of their initial conditions in such a way that an initial (i.e. before bar formation) radial metallicity gradient in the thin stellar disk can be translated into a vertical gradient in the bulge. An initial radial gradient in the thin disk sufficiently steep<sup>4</sup> ( $\sim -0.4$  dex/kpc, as in Martinez-Valpuesta & Gerhard (2013)) would reflect into a vertical gradient along the bulge minor axis similar to that observed (Zoccali et al. 2008; Gonzalez et al. 2011; Gonzalez et al. 2013). In Fig. 2, we present the  $(l, b)$ -mean metallicity maps of our simulated galaxy. The initial radial metallicity profile assigned to the thin stellar disk before bar formation is  $[\text{Fe}/\text{H}] = [\text{Fe}/\text{H}]_0 + \alpha R$ , with  $\alpha = -0.4$  dex/kpc,  $R$  the distance in the plane from the galaxy center, and  $[\text{Fe}/\text{H}]_0 = 0.5$  dex being the metallicity at  $R = 0$ . For the classical bulge, we adopt a gaussian metallicity distribution, with a mean at -0.4 dex, which is the typical metallicity of a spheroid of that mass (see Gallazzi et al. 2005; Lee et al. 2008; Thomas et al. 2010), and a dispersion of 0.3 dex. Similarly to Martinez-Valpuesta & Gerhard (2013): 1) the metallicity maps show a characteristic peanut shape, with the major axis of the peanut elongated parallel to the minor axis of the stellar bar; 2) a vertical gradient (of the order of  $\sim -0.04$  dex/deg in our model, similar to the estimates given in Gonzalez et al. (2013)) can be generated in the bulge. These findings are a consequence of the mapping of thin disk stars into the bulge that has been extensively discussed in Di Matteo et al. (2014): stars born in the innermost galaxy regions (where the metallicity attains the highest values, according to the assumed initial conditions) remain mostly confined there, whilst stars coming from the outer regions of the bar and beyond (up to the bar OLR) are preferentially found at higher latitudes (see, for ex, Fig. 7 in Di Matteo et al. (2014)). Note that the presence of a small classical bulge ( $\sim 10\%$ ) does not have a significant impact on the metallicity map shown in Fig. 2, since the stellar distribution in the boxy bulge is dominated, at all latitudes and longitudes,

<sup>3</sup> Note that a mild velocity gradient with latitude is found for stars at positive or negative longitudes, that is with  $|l| > 0$ . For example, at  $l = -10^\circ$ , the velocity gradient is of about 6 km/s/deg, stars at  $b = -10^\circ$  having a rotational velocity which is about 35 km/s smaller than those of stars at  $b = -4^\circ$ . A similar behavior is found also in observational data, see for example Ness et al. (2013b).

<sup>4</sup> Note that the pure thin disk scenario requires that the initial radial metallicity gradient is steep at all radii. The adoption of a shallower gradient at radii greater than the bulge size, as done by Bekki & Tsujimoto (2011b), can lead to a final vertical gradient significantly weaker than that observed in the MW bulge. We refer the reader to the discussion in Martinez-Valpuesta & Gerhard (2013) on this point.



**Fig. 2.** Metallicity maps of the simulated galaxy in galactic coordinates: *Top panel:* Disk as well as classical bulge stars are included; *Bottom panel:* Disk stars only are shown (see text for the choice of the initial metallicity of disk and classical bulge stars). In both panels, only stars with  $|x| \leq 2.5$  kpc and  $|y| \leq 3$  kpc from the galaxy center have been selected. Some contour levels for the metallicity maps are also reported, with values given in the maps.

by stars originating in the disk (see, for example, top panel of Fig. 11 in Di Matteo et al. (2014)).

The ability of pure bar instability processes, originated in the thin disk, to reproduce the *global* kinematic and chemical characteristics of the MW’s bulge may be considered sufficient to rule out the presence of other components in the inner regions of the Galaxy. In this respect, it seems there is no need to invoke the presence of a massive classical bulge or a thick disk to reproduce the main trends observed. It would be sufficient that at the time of bar formation, the MW thin disk had a steep radial metallicity gradient accompanied by a positive radial gradient of  $[\alpha/\text{Fe}]$  values. If such initial conditions were in place, after the buckling instability, the metal poor,  $\alpha$ -enriched stars would have been preferentially mapped at high latitudes in the bulge, whilst the most metal rich and not  $\alpha$ -enhanced would have stayed preferentially confined closer to the Galaxy midplane, giving rise to the observed vertical metallicity and  $[\alpha/\text{Fe}]$  gradients. In Di Matteo et al. (2014), we have already commented on the weakness of such a scenario: it would imply that the typical metallicity of the MW disk at 4–5 kpc from the Galaxy center was between  $-1$  and  $-1.5$  dex and such low metallicities are never reached in

the MW thin disk (see, for example Fuhrmann 1999; Bovy et al. 2012; Haywood et al. 2013), but are typical of the metal-poor tail of the thick disk and of the MW halo (see, among others, Beers & Sommer-Larsen 1995; Reddy & Lambert 2008; Nissen & Schuster 2010). Here we are interested in exploring the consequences such a scenario would have on the spatial redistribution of stars and on their kinematics, as a function of their chemistry, and to show that the characteristics it would imply do not agree with what we know about the MW’s bulge components.

### 3.2. Failures of a pure thin-disk bar instability scenario

The first consequence of a pure thin-disk bar instability scenario for the MW’s bulge is that *all stars in the bulge fields should be part of the boxy/peanut-shaped structure*, independent on their metallicities. For example, as Martinez-Valpuesta & Gerhard (2013) point out, “the lower limit to the metallicity in the bulge fields would be set by the outer boundary of the part of the disk which participates in the instability”.

To quantify the implications of this scenario, in Fig. 3 we show the distribution of the apparent magnitude of red clump stars, as deduced from the N-body model, at different latitudes along the bulge minor axis. In producing this distribution, we have adopted an absolute magnitude for the clump stars of  $M_K = -1.61$  (Alves 2000) which gives the minimum of the split red clump at  $K=12.9$ .

This distribution is particularly suitable to understand the underlying morphology. The density of a peanut-shaped bar indeed shows some depression in the center, on its minor axis, depression which is more accentuated at higher latitudes. On the line of sight, this produces a bimodal distribution, or a split, in the apparent K-magnitude of the red clump.

In Fig. 3, the distribution of  $K$ -magnitudes at different latitudes is shown for stars in the metallicity ranges:  $[\text{Fe}/\text{H}] > 0$  dex,  $-0.5 \text{ dex} < [\text{Fe}/\text{H}] \leq 0$  dex,  $-1 \text{ dex} < [\text{Fe}/\text{H}] \leq -0.5$  dex, corresponding respectively to populations A, B and C, as defined by Ness et al. (2013a). As in the previous section, the initial radial metallicity gradient is  $\alpha = -0.4 \text{ dex/kpc}$ , and the classical bulge has a median metallicity of  $-0.4$  dex, and a dispersion of  $0.3$  dex. Fig. 3 shows unequivocally that if the MW’s bulge was the result of a pure bar instability mechanism originated in the thin disk, all stars in the bulge should be part of the peanut structure, and in particular also those with  $-1 \text{ dex} < [\text{Fe}/\text{H}] \leq -0.5$  dex should show the split in the distribution of  $K$ -magnitudes. But this is clearly in disagreement with the results presented by Ness et al. (2013a) – and reported also in Fig. 3 –, who observationally found the split only for red clump stars of higher metallicities. Here thus lies the failure of the pure thin disk/bar instability model: on the one hand, for the scenario to be successful, one would require metal-poor,  $\alpha$ -enriched stars to be present in the thin disk before the formation of the bar, in order to participate to the bar instability, be scattered at high vertical distances from the Galactic plane, and, as a consequence, constitute the low metallicity part of the metallicity distribution function; on the other hand, the natural and inevitable consequence of such a hypothesis is that those stars should be part of the peanut structure, while they are not, as, for example, the distribution of  $K$ -magnitudes deduced by the ARGOS survey shows. Note that even adding the contribution of a low mass classical bulge with  $B/D=0.1$ , which has been suggested as the upper limit of any classical bulge in the MW (Shen et al. 2010; Di Matteo et al. 2014), the result is unchanged (cfr left and right columns, Fig. 3): all components, from A to C, would be involved in the peanut, and

show, as a consequence, a split in the distribution of red clump stars. In agreement with the findings of Saha et al. (2012, 2013), such a low mass classical bulge, initially not-rotating, would acquire some angular momentum during the secular evolution (see Fig. 12 in Di Matteo et al. (2014)), but – as we checked – would not show any split in the  $K$ -magnitude distribution, indicating that it does not participate to the bar. Overall, it would leave only very weak signatures in the  $K$ -distribution, and, coupled with an initial steep disk metallicity gradient, it would not erase the characteristic split of the peanut.

The  $K$ -magnitude distribution of red clump stars is only an example of the discrepancy with observations that such a bulge formation scenario would imply. Also the *detailed* kinematic characteristics of a bulge formed only via bar instability in a pre-existing thin stellar disk would not agree with observations. To elucidate this point, in Fig. 4 we show the velocity curves and velocity dispersions profiles that stars in the three different metallicity bins formerly defined would have in such a scenario. Similarly to observations, which often lack proper motions measurements for bulge stars, only the radial component of the velocity is shown in this plot. For comparison, the velocities and velocity dispersions observed for populations A, B and C, as defined by Ness et al. (2013a), are also shown. If all stars in the bulge MDF had a thin disk origin, according to Fig. 4, the following kinematic trends should be observed:

1. the velocity dispersion should increase with decreasing metallicity, in such a way that population C should be a warm replica of populations A and B, that is it should show velocity dispersions profiles similar to those of the stellar populations associated to the bar, but shifted to higher absolute values
2. the rotational velocity should increase with decreasing metallicity, continuously from super-solar metallicities to  $[\text{Fe}/\text{H}] = -1$  dex.

As explained in Di Matteo et al. (2014), the trends at points 1. and 2. are the simple consequence of the differential mapping of a thin disk into a boxy bulge, the larger the birth radius of stars, the higher their rotational velocity and velocity dispersion.

In Di Matteo et al. (2014), comparing these trends with the results by Ness et al. (2013b), we have concluded that the MW's bulge population B ( $-0.5 \text{ dex} < [\text{Fe}/\text{H}] \leq 0 \text{ dex}$ ) must have on average a more external disk origin than population A ( $[\text{Fe}/\text{H}] > 0 \text{ dex}$ ). Indeed, according to the ARGOS observations reported in Fig. 4, and to the discussion in Ness et al. (2013b), population B shows a higher rotational velocity and similar velocity dispersions profiles (but with higher absolute values) than population A, as it would be the case if component B formed on average further out from the galaxy center than component A.

However, for the purpose of the present discussion, we want to emphasize that points 1. and 2. also lead us to exclude the idea that the more metal poor population C ( $-1 \text{ dex} < [\text{Fe}/\text{H}] \leq -0.5 \text{ dex}$ ) can have an origin in the old MW thin disk. From Martinez-Valpuesta & Gerhard (2013) and Sect. 3.1, we have indeed learnt that a steep metallicity radial gradient in the thin disk is necessary before bar formation occurs, in order to reproduce a vertical gradient along the bulge minor axis, as currently observed. Thus in this scenario, the metal poor population C would have been initially –i.e. before the onset of the bar instability – a thin disk population located further out from the center than populations A and B. The subsequent bar vertical instability process would have scattered these stars to high distances from the plane, leading this component to have

kinematic properties similar to those found in Fig. 4 for the most metal poor stars. That is, in this scenario C should show a rotational velocity greater than that of populations A and B, and its velocity dispersions would be a simple warm replica of those of the most metal rich populations. But this is excluded by the observational data (Ness et al. 2013b), which shows velocity dispersions that are constant both with longitude and latitude, and a rotational velocity similar to that of population A and B.

Overall, our results point to the necessity of making use of both the kinematic and elemental abundance information from the various bulge components to understand its origin. While this is obviously true, why is it that most analyses based on N-body simulations have not been able to capture the kinematically warmer component that is apparent in the data? The reason is simple. Among the main components A, B and C found in the MW's bulge, most of the numerical models (Shen et al. 2010; Kunder et al. 2012; Ness et al. 2013b; Zoccali et al. 2014), including this work, have been essentially able to capture only component B.

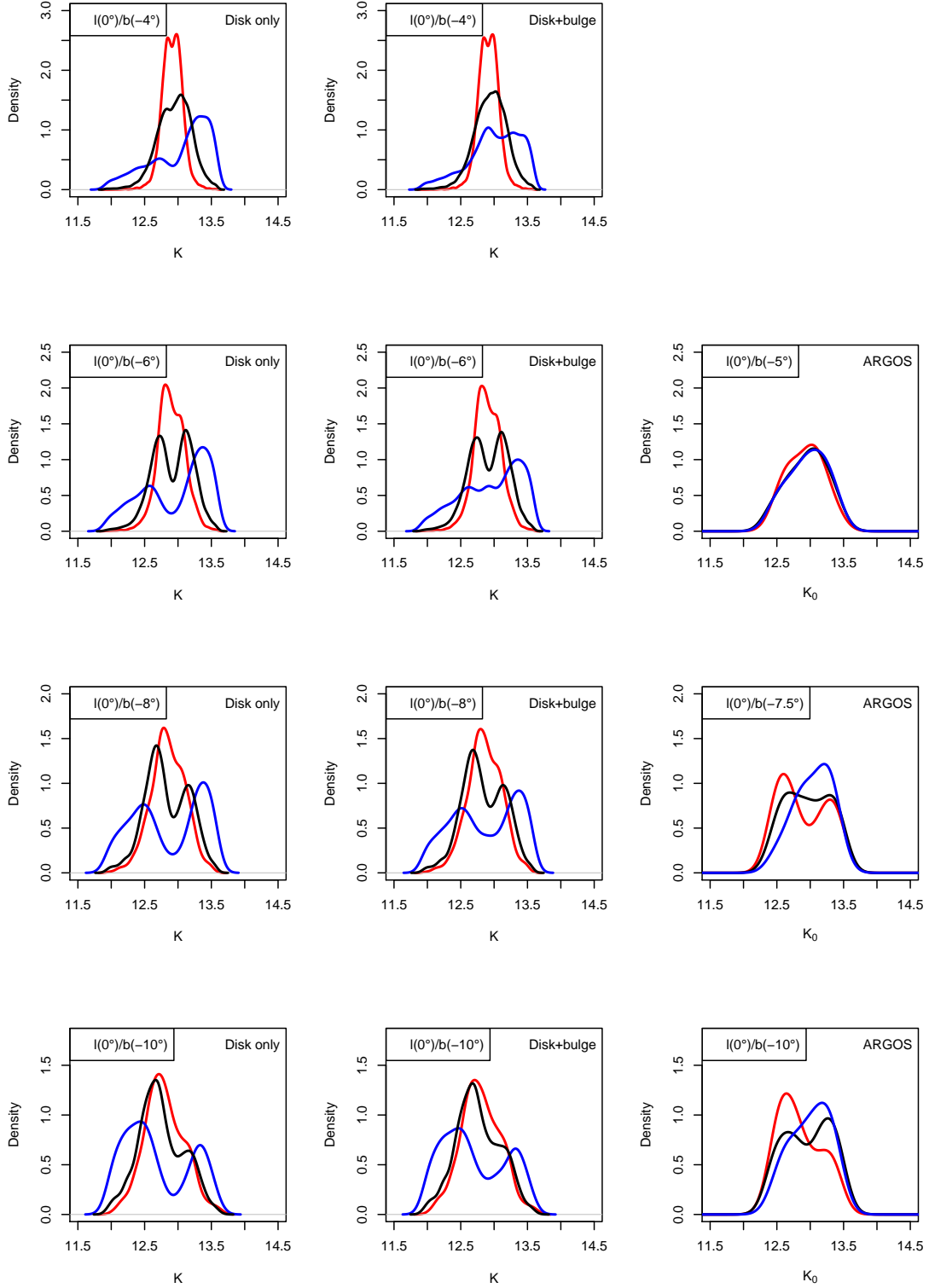
B constitutes the backbone of the MW's bulge (see Ness et al. 2013a) and the bulge global kinematic trends are well represented by population B (see Figs. 3 and 6 in Ness et al. 2013b). Thus a pure thin disk N-body model which fits the global kinematics of the MW's bulge by means of a single stellar population is essentially fitting, and capturing, the properties of population B only<sup>5</sup>. It is only by modeling both the peanut-shaped components A and B that N-body simulations can point out the existence of a kinematically warmer component like C. This because the inclusion of component A would result in a bulge with a global kinematics colder than what generally found in models which reproduce B only, and, as a consequence, it would be possible and even necessary to accommodate a kinematically warmer component to fit the global trends.

#### 4. Discussion: The Milky Way as a pure (thin+thick) disk galaxy

If a pure thin disk/bar instability scenario for the MW's bulge can be rejected, does this imply that our Galaxy is not a pure disk galaxy, as it was suggested by Shen et al. (2010)? This question is tightly related to this second one: What is the nature of the kinematically hotter component C found in the inner Galactic region, whose origin cannot be related to the thin disk?

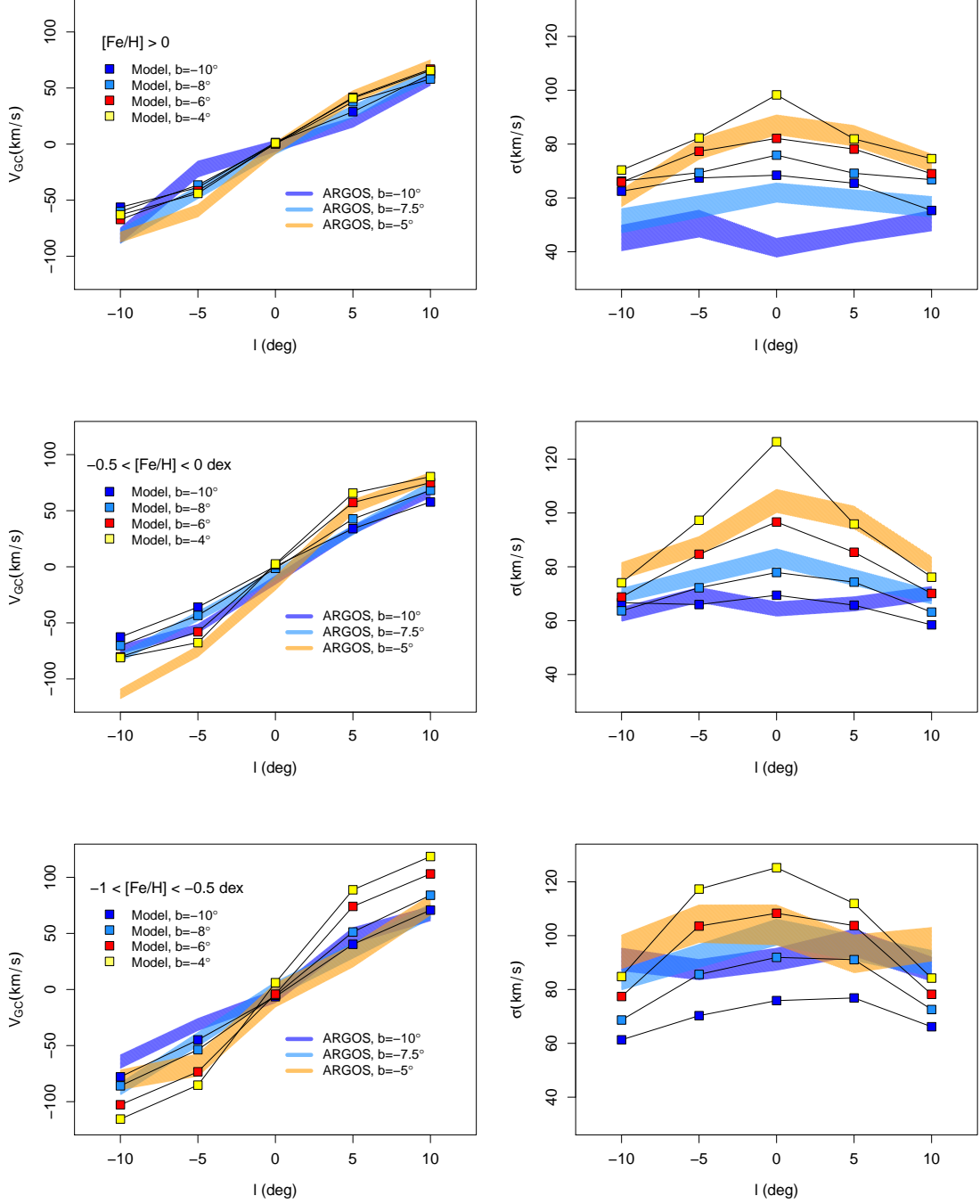
The answer to this second question is still somewhat speculative at this stage, but it is worth suggesting that the growing evidence and recent results should inspire us to critically revise our view of the populations and components of the MW. From the work of Bensby et al. (2011) and Bovy et al. (2012) we learn that the  $\alpha$ -enhanced, metal-poor population of the Galaxy, coincident with the thick disk at the solar vicinity, has a scale length of about 1.8 kpc, that is a factor of about 2 less than previous estimates (see for example Jurić et al. 2008). This finding, coupled with the thin/thick disk local normalization, implies that the thick disk is under-represented at the solar vicinity, and it is

<sup>5</sup> In our model, this can be appreciated in Figs. 1 and 4: from Fig. 4 it is evident that the modeled population B is the only which satisfactory captures the kinematics of the corresponding observed stellar component (both components with  $[\text{Fe}/\text{H}] > 0$  and  $[\text{Fe}/\text{H}] < -0.5 \text{ dex}$  do not capture the kinematics of the corresponding populations A and C observed by ARGOS); comparing Fig. 4 with Fig. 1, it is evident that the kinematics of modeled component B is representative of the global bulge kinematics.



**Fig. 3.** (Left and middle columns): K-band magnitude distributions of red clump stars in the modeled galaxy at different latitudes along the bulge minor axis. An initial radial metallicity profile  $[\text{Fe}/\text{H}] = 0.5 - 0.4R$  in the disk is assumed, similarly to Martinez-Valpuesta & Gerhard (2013). Three different metallicity bins are then shown:  $[\text{Fe}/\text{H}] > 0$  (red curve),  $-0.5 < [\text{Fe}/\text{H}] \leq 0$  (black curve),  $-1 < [\text{Fe}/\text{H}] \leq -0.5$  (blue curve), similarly to populations A, B and C as defined by Ness et al. (2013a). Disk stars only are shown in the left panel, while all (i.e. disk and classical bulge) stars are shown in the right panel. In all panels, stars with  $(l, b)$  in the interval  $(l_0, b_0) \pm (\Delta l, \Delta b)$  are shown, with  $\Delta l = \Delta b = 1^\circ$  and  $(l_0, b_0)$  as given in the top-left corner. (Right column):  $K_0$ -band magnitude distributions of red clump stars at different latitudes along the bulge minor axis from the ARGOS survey. See Ness et al. (2013a) for details.





**Fig. 4.** Rotation curve (*left panels*) and velocity dispersions (*right panels*) a boxy bulge formed from a thin stellar disk (square symbols) compared to ARGOS data (colored curves). In the N-body model, only stars at  $|x| \leq 2.5$  kpc and  $|y| \leq 3$  kpc from the galaxy center are shown. An initial radial metallicity profile  $[\text{Fe}/\text{H}] = 0.5 - 0.4R$  in the disk is assumed, similarly to Martinez-Valpuesta & Gerhard (2013). Three different metallicity bins are shown, from top to bottom in decreasing  $[\text{Fe}/\text{H}]$ , corresponding to the populations A, B and C as defined by Ness et al. (2013a). For each plot, four different latitudes are shown for the modeled galaxy:  $b = -4^\circ$  (yellow squares),  $b = -6^\circ$  (red squares),  $b = -8^\circ$  (pale blue squares),  $b = -10^\circ$  (dark blue squares). For comparison, ARGOS fields at  $b = -5^\circ$  (orange curve),  $b = -7.5^\circ$  (pale blue curve),  $b = -10^\circ$  (dark blue curve) for populations A, B and C are also given. The thickness of the curves corresponds to the  $\pm 1\sigma$  error in the observational data.

rather mostly concentrated towards the inner Galactic regions, where it can become comparable to the thin disk mass (see discussion in Snaith et al. 2014a, and also Fuhrmann et al. (2012)). The finding that the thick disk mass is comparable to that of the thin disk is not only the result of the simple structural arguments

given previously, it finds a strong support, and independent confirmation, in the recent work by Snaith et al. (2014a,b). Snaith et al. modelled the  $[\alpha/\text{Fe}]$ -age relation recently discovered for disk stars in the solar vicinity (Haywood et al. 2013) with a simple closed-box evolutionary scenario. Snaith et al. showed that:

i) the thick disk formed during the most intense phase of star formation in the Galaxy; ii) this phase, which lasted from about 13 to 8-9 Gyr ago, formed as many stars as the subsequent, more quiescent, phase of star formation in the disk, that proceeded from 8-9 Gyr ago to the present epoch during which the thin disk was formed. Note that the findings of Snaith et al. (2014a) are in substantial agreement with the independent work of van Dokkum et al. (2013), who, on the basis of abundance matching techniques, followed the evolution of “MW-like” progenitors from  $z=2.5$  to the present epoch, concluding that these galaxies formed half of their stellar mass before redshift 1 (see Snaith et al. 2014a, and also Lehnert et al. (2014)). Their results indicate that before  $z=1$ , these galaxies were growing at all radii, with the inner regions growing at the same rate as the outer regions. As van Dokkum et al. (2013) point out, in these MW-analogues “we do not see high-density naked bulges at  $z \sim 2$  around which disks gradually assembled. .... The evolution from  $z = 2.5$  to  $z = 1$  is strikingly uniform: the profiles are roughly parallel to one another, and rather than assembling only inside out the galaxies increase their mass at all radii. This is in marked contrast to more massive galaxies, which form their cores early and exclusively build up their outer parts over this redshift range.” The interpretation of van Dokkum et al. (2013) results, in light of the works by Snaith et al. (2014a,b) and Lehnert et al. (2014), strongly suggest that:

- in these high redshift MW analogues we are witnessing the formation of thick disks;
- these galaxies were not forming at those times any significant classical bulge.

While we refer to Lehnert et al. (2014) for a detailed discussion on the properties of the MW at high redshift, here we emphasize that, if confirmed, this formation and evolutionary scenario would be substantially different from those suggesting that the old, metal-poor,  $\alpha$ -enhanced population of the MW’s bulge can be explained by a classical bulge or old spheroid (Babusiaux et al. 2010; Gonzalez et al. 2011; Hill et al. 2011; Uttenthaler et al. 2012; Zoccali et al. 2014). Recently, for example, Zoccali et al. (2014) suggested that the oldest component of MW’s bulge resembles a low massive early-type galaxy, with properties similar to those of current early-type galaxies, as described by the SAURON and ATLAS3D samples (Bacon et al. 2001; Cappellari et al. 2011). Whilst it is true that an old thick disk can resemble for many aspects a fast rotating early-type system, the classical bulge/old spheroid scenario would imply that what we observe in the MW inner regions cannot be explained essentially on the basis of the known Galactic populations at the solar vicinity (i.e. thin and thick disks and only very marginally by a stellar halo), but rather requires to include an additional kinematically hot component, not negligible in terms of mass, in the central galactic regions. The disagreement between the two scenarios is thus much more than a simple semantic difference. Even the advocacy (Zoccali et al. 2014) of an instability mechanism via clumps formation and coalescence in the galaxy center (Noguchi 1999; Immeli et al. 2004; Elmegreen et al. 2008) to form the MW’s bulge raises some doubts. The most recent models show that this evolutionary channel is inefficient in forming massive ( $B/D > 10\%$ ) classical bulges in MW-like galaxies (Bournaud et al. 2014). Moreover, N-body simulations of classical bulge formation by clumpy instabilities show that these structures are usually slow rotators (see Elmegreen et al. 2008), a property hardly reconcilable with the fast rotation of population C (see Ness et al. 2013b). These considerations, coupled with the fact that the metallicity of component C is unlikely for a classical

bulge of  $\sim 10^{10} M_{\odot}$  (see discussion in Di Matteo et al. 2014, and references therein) strongly suggest the possibility that the MW’s bulge is the result of the simple mapping of the Galactic (thin + thick) disk in the central regions of the Galaxy, with the kinematically coldest part of the disk captured in the bar vertical instability (and thus mapped into populations A and B) and the kinematically hottest component forming population C (see also the discussion in Ness et al. 2013b). Note that N-body simulations of boxy/peanut shaped bulges formed in galaxies containing both a thin and a thick stellar disk seem to support this scenario, by showing that the strength of the peanut shaped structure depends on the origin of the stars, with thin disk stars showing a more prominent peanut-shaped bar than stars originating in the thick disk (see Bekki & Tsujimoto 2011a, their Fig. 10). These (thin+thick) disk models can also reproduce both the observed cylindrical rotation and vertical metallicity gradient of the Galactic bulge reasonably well (Bekki & Tsujimoto 2011b).

Even if further models are needed to test if this scenario is able to reproduce the chemo-kinematic trends unraveled by the most recent spectroscopic surveys of the Galactic bulge, we emphasize that currently:

1. solar vicinity data (see Fuhrmann et al. 2012; Haywood et al. 2013; Snaith et al. 2014a,b)),
2. as well as Galactic kpc-scale observations (Bensby et al. 2011; Bovy et al. 2012),
3. the redshift evolution of MW-like analogues (van Dokkum et al. 2013),

all seem to imply a substantial role of thick disks in the evolution of MW-like galaxies, a role still underestimated in the current debate on the nature of the MW’s bulge populations. The recent findings of strong similarities between the  $[\alpha/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  trends of solar vicinity thick disk stars with the  $\alpha$ -enhanced, metal-poor population of the bulge (Meléndez et al. 2008; Alves-Brito et al. 2010; Bensby et al. 2011, 2013; Gonzalez et al. 2011), if confirmed with larger high resolution spectroscopic samples, would be a strong additional support to this scenario.

## 5. Conclusions

By analyzing a high resolution, N-body simulation of a bulge formed via a simple bar instability mechanism in a thin disk:

- We have shown that such a scenario is not compatible with the known structural and kinematic properties of the main populations of the Galactic bulge.
- In particular, we emphasize that *global* kinematic and metallicity trends alone are not sufficient to constraint the MW’s bulge formation scenario. It is only by coupling kinematic and abundances information that N-body models are able to reject a pure thin disk/bar instability process to explain the formation and characteristics of the MW’s bulge.
- Thus, in disagreement with recent suggestions, we conclude that the Milky Way bulge is not purely a bar originated in a kinematically cold stellar disk and seen edge-on. Its components did not all originate in the thin disk.

On the basis of a number of recent observational evidence, recalled in this paper, we suggest that the metal poor,  $\alpha$ -enhanced population which is present in the bulge, but which is not part of the peanut structure, is the same population known at the solar vicinity as the old thick disk.



## Acknowledgments

The authors acknowledge the support of the French Agence Nationale de la Recherche (ANR) under contract ANR-10-BLAN-0508 (GalHis project). MN acknowledges funding from the European Research Council under the European Unions Seventh Framework Programme (FP 7) ERC Grant Agreement n. [321035]. Support for ONS was partially provided by NASA through the Hubble Space Telescope Archival Research grant HST-AR-12837.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. The authors are grateful to N. Stefanovitch for his technical help. PDM thanks F. Matteucci and C. Morossi for the organization of the stimulating conference on the "Formation and Evolution of the Galactic Bulge" (Sesto, Italy, January 2014), where many of the ideas presented in this paper took shape. PDM is grateful to F. Bournaud for an enriching discussion on the current state of knowledge of clumpy disk galaxies. We thank the referee for a very constructive report, which greatly helped us to clarify our results.

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